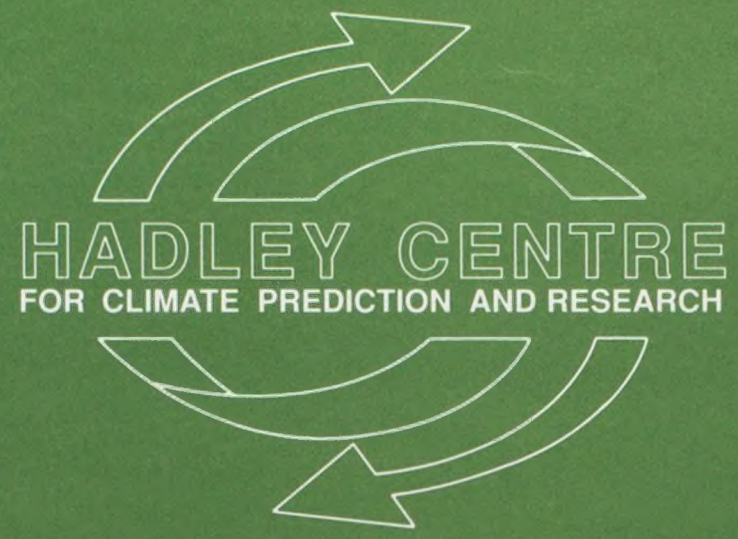

Climate Modelling :

Achievements and Prospects

by

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Climate modelling: achievements and prospects

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(Presidential address: delivered 17 June 1998)

SUMMARY

The significant progress made with coupled (atmosphere-ocean) general circulation models (CGCMs) over the past decade or so is discussed in the context of the reports of the Intergovernmental Panel on Climate Change (IPCC). In IPCC (1990), most climate-change GCMs were atmospheric general circulation models coupled to 'slab' ocean models and being used only to determine the 'equilibrium' climate response to specified increases in carbon dioxide. The wide range of estimates of their 'climate sensitivity' is discussed, especially in the context of the uncertainty introduced by model sensitivity to representations of cloud. The modelling focus then moved to transient-response, climate-change experiments. These and the related modelling problems are noted; as are the simultaneous growing awareness and improved quantification of a range of natural and human-induced radiative forcings. The consequent inclusion of this information in CGCMs to study the detection and attribution of climate change, leading to the IPCC (1995) statement that 'the balance of evidence suggests that there is a discernible human influence on global climate', is also discussed.

A significant modelling breakthrough since IPCC (1995) is the capability of a few CGCMs to produce stable and realistic climate (control) simulations without using artificial 'flux adjustments'. This is illustrated with results from such a Hadley Centre model (HadCM3). In conclusion, a brief perspective is given of high-priority modelling developments and applications to be addressed over the next decade.

KEYWORDS: Climate change Climate modelling Climate prediction Global warming Greenhouse effect Intergovernmental Panel on Climate Change

1. INTRODUCTION

The concern about climate change resulting from human activities is supported most strongly by results from mathematical climate models. They are essential for furthering our understanding of how the climate system works, for detecting climate change and for identifying possible 'fingerprints' of climate change resulting from an enhanced greenhouse effect, and other human or natural influences. In particular, they are also essential for predicting the climate changes to be expected as the likely consequences of different scenarios of future emissions of greenhouse gases and other factors that could alter the atmosphere's radiative balance. The type of model which holds out the prospect of dealing satisfactorily with the complexity of the climate system, its current state and future evolution both globally and regionally, is the so-

called three-dimensional, global, coupled (atmosphere-ocean) general circulation model (CGCM). This is based on the mathematical equations which describe the motions and physical processes in the atmosphere and the oceans, and how the various components of the climate system interact with each other. My aims in this address are, firstly, to indicate the significant progress made in climate modelling with CGCMs during effectively the last decade and, secondly, to identify some of the prospects for continuing progress over the next. To do so I shall focus on the development of the models' capabilities and how they are used, rather than their validation or climate-change predictions *per se*.

The development of climate modelling since 1988 is linked inextricably with the parallel evolution of the review process of the Intergovernmental Panel on Climate Change (IPCC) and its influence in providing the authoritative, timely and up-to-date scientific advice needed to inform the deliberations surrounding the United Nations Framework Convention on Climate Change (UN FCCC) (see Fig.1). The IPCC was established in 1988 by two United Nations' bodies, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP). Three working groups were quickly established, one to deal with the science of climate change, one with impacts and the third to deal with policy responses. Whereas the other two working groups have had their remits changed as the assessment process has evolved, the Scientific Assessment Working Group (WGI) has been maintained as it was first established and has published four major reports to date (IPCC 1990, 1992, 1994, 1995). The first, in 1990, was the first truly comprehensive scientific assessment of climate change, and served as the scientific basis for negotiating the UN FCCC; I shall use this as my starting point (section 2). The Convention process was assisted further by the supplementary report, produced for the Earth Summit in Rio de Janeiro in 1992, and a more specialised report, on the radiative forcing of climate change and an evaluation of the IPCC IS92 emissions scenarios, in 1994. The second full scientific assessment was produced at the end of 1995. I shall use these three particular IPCC scientific reports as 'milestones' for the results from, and progress with, climate models that I shall discuss in section 3.

Also in section 3, I shall indicate the further significant progress made since the second IPCC full assessment in 1995. I shall then outline, in section 4, the prospects for continuing progress in climate modelling, identifying our immediate problems and priorities, and then conclude (section 5).

I wish to acknowledge at the outset the generous and valuable help I have received in preparing this address from several colleagues at the Hadley Centre, Meteorological Office (see acknowledgements).

2. THE IPCC SCIENTIFIC ASSESSMENT 1990

(a) Equilibrium-response climate-change experiments

The state-of-the art atmospheric general circulation models (AGCMs) reported in IPCC (1990) were already demonstrating considerable skill in reproducing many of the large-scale features of the current climate and I shall take for granted throughout

this address that such validation is a prerequisite for any model to be used for climate-change experiments. However, at that stage, most of the GCMs available and being used for climate-change studies were AGCMs coupled to simple representations of the uppermost layer (typically 50-100m deep) of the ocean (so-called 'mixed-layer' or 'slab' ocean models). These were used principally to determine the 'equilibrium' climate response to increased concentrations of atmospheric greenhouse gases (more particularly, carbon dioxide), this being the response obtained when the model has come into statistical equilibrium with the prescribed and enhanced levels of carbon dioxide.

IPCC (1990) gives a comprehensive list of such models already used in equilibrium-response experiments (almost exclusively to an instantaneous doubling of the atmospheric concentration of carbon dioxide). Most of the 22 separate references from nine distinct institutes have relatively-coarse resolution AGCMs. Only three models (from the Canadian Climate Center, Geophysical Fluid Dynamics Laboratory (GFDL, Princeton, USA) and UK Meteorological Office (UKMO)) are classed as 'high resolution', the highest being that of the UKMO's 11-layer AGCM with a 2.5^0 by 3.75^0, latitude-longitude grid. Although clearly limited for climate-change studies, such experiments were useful for evaluating the asymptotic limit for climate change following a prescribed change in greenhouse-gas concentrations, and also for exploring the sensitivity of the models to the representation of various processes and boundary conditions.

The long-term change in globally-averaged surface air temperature following a doubling of carbon dioxide is referred to as the *climate sensitivity*. This is acknowledged as an important model (and climate) characteristic and estimates from different models are documented in IPCC (1990). Although the spatial patterns of such equilibrium responses were found to vary from model to model, a number of consistent, large-scale changes were beginning to emerge that could be explained in physical terms. For example: the simulated changes in temperature varied considerably with latitude, longitude and season; the largest warmings were over sea-ice in winter and smallest over sea-ice in summer; there was a marked land-sea contrast and considerable geographical variation in warming within individual continents; the troposphere warmed and the stratosphere cooled. However, it was also fully acknowledged that the models' regional responses showed considerable differences.

A major problem facing the modeller is to identify the significant so-called feedback mechanisms in the climate system and to determine the sign and size of their various effects. Taking into account feedbacks, such as those due to water vapour, snow and ice albedo, and cloud radiation, the IPCC (1990) estimated the climate sensitivity to lie within the range 1.5 - 4.5K (see Table 1).

TABLE 1. ESTIMATES OF THE EFFECTS OF INTERNAL FEEDBACKS ON THE EQUILIBRIUM WARMING IN RESPONSE TO A DOUBLING OF CARBON DIOXIDE

Process	**Warming (K)**
No feedbacks (other than re-establishment of new equilibrium as a result of black-body cooling)	1.2
+ Water vapour feedback	1.7
+ Changes in snow, ice and clouds	1.5 - 4.5

The state-of-the-art climate models in IPCC (1990) also gave equilibrium globally-averaged surface temperature responses to a doubling of carbon dioxide which varied by a factor 3 or more. This was consistent with previous estimates of the range, and 2.5K was chosen as the best estimate, based on somewhat subjective considerations of model simulations, feedback analyses and observational evidence over the past century.

(b) Cloud-climate feedbacks

The biggest single contribution to the range of uncertainty in the climate sensitivity (Table 1) comes from our inadequate understanding of the feedback processes involving the interaction of clouds with both solar and terrestrial radiation. Modelling studies at the Meteorological Office (and elsewhere) highlighted that the response of models to changing the concentrations of the greenhouse gases is very sensitive to the treatment of clouds (see Mitchell *et al.* (1989) and Senior and Mitchell (1993)). Typical AGCM sensitivity studies were carried out with three different cloud schemes. The first was a standard, simple scheme in which cloud cover is a function of relative humidity. The second was a more complicated prescription including an explicit cloud water variable and distinguished between the properties and the precipitation processes associated with water and ice clouds. The third scheme allowed, in addition, the cloud radiative properties themselves to depend on the liquid-water content of the clouds. The result was that the average equilibrium surface warming in response to an effective doubling of carbon dioxide was reduced from 5.2K to 2.7K in going from the first to the second scheme, and reduced further still to 1.9K when the third scheme was used. Although the second and third schemes are more elaborate and include descriptions of more of the physical processes, there was no good cause to believe at the time that they were necessarily more accurate than the simple, relative-humidity based scheme.

The spread 1.9K to 5.2K represents a factor of 2.7 in that model's climate sensitivity in response to simply changing its representation of clouds. This result is compatible with a contemporary study (Cess *et al.* 1989) in which 14 AGCMs were compared and found to have a three-fold variation in global climate sensitivity caused largely by different cloud feedbacks. The uncertainty in how to formulate clouds posed then, and continues to pose now, a formidable obstacle to reliable climate prediction even in the equilibrium global-mean sense, let alone in the context of transient-response, regional predictions.

(c) Transient-response climate-change experiments

Transient-response, climate-change experiments are those which examine the evolution of the climate response to a gradual (*i.e.* time-dependent) change in the greenhouse gases, or any other radiative forcing factors. To simulate fully such transient behaviour it is necessary to use a CGCM with a full-depth ocean capable of modelling ocean dynamics, physics and the global circulation.

In the preparation of IPCC (1990) only a few such studies with 'fully-coupled' GCMs were beginning to emerge. This was primarily due to a lack of dedicated computer resources at that time. Four climate-change experiments with CGCMs are listed in IPCC (1990), from GFDL, the National Center for Atmospheric Research (NCAR, Boulder, USA), the Max-Planck Institute for Meteorology (MPI, Hamburg, Germany) and the Meteorological Institute at the University of Hamburg. All these CGCMs had generally coarse resolutions in both their atmosphere and ocean components; the overall best-resolved model being that of MPI (T21 spectral horizontal resolution with 19 levels in its atmosphere model, and a 4^0 horizontal resolution with 11 levels in its ocean model). However, only one of the experiments had been conducted for a long-enough integration period to reach (at least) a doubling of the model's initial concentration of atmospheric carbon dioxide. This is accredited to GFDL (Stouffer *et al.* 1989) who had integrated their CGCM for 100 years with a continuous 1% per annum compound increase in its concentration of atmospheric carbon dioxide (used as a surrogate for all the 'well-mixed' greenhouse gases in the model). This chosen emissions scenario is close to the so-called Business-as-Usual (BaU) scenario defined in IPCC (1990).

At the 'decade of doubling of carbon dioxide' in the GFDL transient-response experiment the regional patterns of temperature change generally resembled those of the corresponding equilibrium-response with an AGCM and mixed-layer ocean model, but were everywhere reduced in magnitude. At the time of doubling of the carbon dioxide in the transient experiment, the globally-averaged temperature response was about 60% of the corresponding equilibrium response. However, the transient response was notably much less than the equilibrium response in specific areas, such as the north-west Atlantic, to the south of Greenland and over the Southern Ocean around Antarctica This is explainable in terms of the inclusion of a full-depth model of the ocean in the CGCM and its consequent ability to simulate both the thermal inertia and the effects of changes in ocean circulations. In the tropical and mid-latitude regions the modelled warming in the oceans is confined to the surface

layers, but nearer the poles it extends through the ocean. In these areas, cold, saline water sinks to the ocean bottom in winter, providing a direct link between the atmosphere and the deep ocean and a mechanism by which the deep ocean can respond relatively rapidly to surface changes. These diagnosed differences between the equilibrium and transient surface-temperature warmings, most evident in the polar and sub-polar regions especially over the oceans, are generally consistent with our understanding of the deep ocean circulation.

Also noted in the transient-response experiments was a small lag (of about 10 years in the GFDL experiment) before any noticeable warming appears to take place. This phenomenon was also to become apparent in the transient-response experiments conducted by others and became known as the 'cold start' problem. In the climate-change experiments *circa* 1990, the CGCMs were brought to (near) equilibrium for present-day greenhouse-gas forcing and then subjected to a sudden change in the rate of forcing (in this case due to a 1% per annum increase in carbon dioxide concentration) at the start of the transient-response phase of the experiment. This contrasts with what happens in the real climate which has already experienced steadily increasing forcing due to the greenhouse gases for well over a century before reaching present-day conditions. The difference between the responses with and without allowing for the history of the forcing to date is known as the 'cold start'. It was an artefact of the limited modelling methodology employed at the time, including, probably, deficiencies in the initial spin-up of the CGCM towards an equilibrium state. However, more experiments were really needed to diagnose its causes fully. To simulate rates of climate change over the next few decades, it is necessary to allow for the heating that has built up due to past changes in radiative forcing.

Further technical problems noted in IPCC (1990) included, general issues of spinning-up the CGCM to (near) equilibrium and then running in coupled mode, and the need to resort to 'flux-adjustments' to prevent substantial 'climate drift' in the sea surface temperatures in such models. These issues will also be returned to later.

In IPCC(1990), it was simply not feasible to use CGCMs to investigate the climate consequences of the four emissions scenarios generated by the IPCC Working Groups. Instead, simpler box-diffusion-upwelling models were used. These simulate the delaying effect of the oceans and contain highly-simplified physics but can be calibrated to give similar results to the globally-averaged responses from GCMs. They were used to produce estimates of the evolution of the temperature responses for three values of climate sensitivity (High, Medium, Low) corresponding to the global equilibrium surface temperature responses to doubling of carbon dioxide of 4.5K, 2.5K and 1.5K, respectively, as discussed earlier. For medium sensitivity and the BaU scenario, the globally-averaged temperature rise was predicted to be about 0.3K per decade (see the IPCC line in Fig. 2).

(d) Key research areas

Many areas of deficiency, sensitivity and uncertainty in climate modelling were already known and identified in IPCC (1990). In this context, I also recommend the comprehensive discussion by Houghton (1991) of the then state-of-the-art weather and climate models in relation to their predictive capabilities. Particular needs included:

(i) increased resolution in CGCMs;

(ii) better validation of CGCMs and their atmosphere and ocean components. This was handicapped by a lack of suitable data, both from observations and the models;

(iii) more experience with the design and implementation of experiments with CGCMs, with particular regard to the need to avoid substantial climate drift, as reflected in the sea-surface temperature, and the use of artificial flux adjustments, and also to address general coupling issues, including spin-up to (near) equilibrium and the cold-start problem;

(iv) improved understanding and representations in CGCMs of small-scale processes. In particular, more information is needed about clouds (primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing), convection, ocean circulation, the interaction of the atmosphere with the oceans, land, the biosphere (on the land and in the oceans) and the cryosphere, the chemical cycles within the atmosphere, and the biogeochemical cycles in the oceans; and

(v) better understanding and quantification of the uptake and release of the greenhouse gases, and their chemical reactions in the atmosphere, and of other forcing factors which could influence past and future climates; in particular, variations in the output of solar energy, volcanic aerosols, and aerosols in the lower atmosphere, mainly from industrial sulphur emissions.

On this last point, note that sulphur dioxide emitted in industrial processes can result in the formation of sulphate particles which typically remain in the atmosphere for a few days before they are washed out by rain. It was already recognised that sulphate aerosols have two effects, both of which are difficult to quantify but which may be significant particularly at the regional level. The first, direct effect of such particles is that they reflect some of the incident sunlight back to space, thus effectively cooling the surface, an effect opposite to that of the greenhouse gases. The second is an indirect effect whereby the aerosols affect the microphysics of clouds leading to an increased cloud reflectivity. It was argued that both these effects might lead to significant regional cooling. Therefore decreases in industrial sulphur emissions might give rise to increases in global temperatures.

3. PROGRESS IN CLIMATE MODELLING SINCE 1990

(a) The IPCC Supplementary Report 1992

With the CGCM emphasis now on transient-response, climate-change experiments, IPCC (1992) contained the results of such studies from four centres, *viz.*, GFDL, NCAR, MPI and the Hadley Centre for Climate Prediction and Research (Meteorological Office, Bracknell, UK). The four models used differed in their horizontal and vertical resolutions, particularly in their ocean components, but all were relatively-coarsely resolved. The highest overall resolution of the four was that of the Hadley Centre (*i.e.* UKMO) model. There were also differences in the greenhouse-gas emissions scenarios used by the models: MPI used the IPCC (1990) BaU scenario; GFDL and the Hadley Centre used 1% per annum compound increase in carbon dioxide concentrations; and NCAR used a 1% per annum simple (*i.e.* linear) increase in carbon dioxide. These give different times to reach a doubling of the initial carbon dioxide concentrations. In this respect, an important point to note is that the responses were dominated by the large spread in climate sensitivities across the models. These range from 2.6K (MPI) to 2.7K (Hadley Centre) to 4.0K (GFDL) to 4.5K (NCAR), which reflect a considerable portion of the IPCC's considered range of uncertainty in climate sensitivity of 1.5 - 4.5K.

In the context of the evolution of the globally-averaged surface temperature in response to either the IPCC BaU scenario, or a scenario very close to that (*i.e.* a 1% per annum compound or linear increase in carbon dioxide concentrations), these models produced fairly consistent results and served, in general, to give added confidence to the corresponding findings of IPCC (1990) (see Fig. 2). Under the BaU scenario of future emissions of greenhouse gases, that report estimated an increase in globally-averaged temperature of about 0.3K per decade. IPCC (1992) not only confirmed this but also continued to emphasise the considerable uncertainties that remained in that estimate and in the regional detail of likely future climate change. In particular, it also confirmed the substantial regional variations obtained in the models' responses to increasing greenhouse gases. In keeping with the earlier transient-response, climate-change experiments analysed in IPCC (1990), these show marked asymmetry between the hemispheres, a marked land-sea contrast, and considerable geographical and seasonal variations in warming within individual continents. In particular, because of the nature of the deep ocean circulations in coupled models (discussed above), parts of the high-latitude southern oceans actually showed some cooling in the early stages of the experiments and throughout the integrations there was little or no warming around Antarctica and south of Greenland.

Although the four CGCM transient-response experiments reported in IPCC (1992) agreed reasonably well in some of their gross characteristics, there was much less agreement in the detail of their regional responses and confidence in regional climate patterns based on CGCM output remained low. However, new techniques were being developed *viz.*, high-resolution, regional climate models nested in and driven by large-scale GCMs, or alternatively interpolating GCM results to smaller scales using statistical methods (correlating regional climate with the large-scale flow). Both methods showed promise, but insufficient studies had been completed to give an improved global picture of regional climate change due to increases in greenhouse

gases. In any event both methods depend critically on the quality of the large-scale flow in the GCM.

By IPCC (1992) more experience had also been gained with difficult modelling problems such as flux adjustment, spin-up and the cold start, with flux adjustment acknowledged as one of the main concerns about the use of CGCMs for climate-change studies. In this context, the prime concern was that the substantial adjustments to surface fluxes at the air-sea interface, used to varying degrees in order to achieve a realistic simulation of present climate, might distort the models' responses to small perturbations such as those associated with increasing greenhouse gases. The MPI model employed such flux adjustments to the surface fluxes of heat, water and momentum, whereas no adjustment to momentum was needed in the GFDL and Hadley Centre models. In contrast, the NCAR model used no flux adjustments, but had to contend with a large climate drift in its simulations.

The short initial delay in the global warming response exhibited by the GFDL model (IPCC 1990) was more pronounced in the other three models. Figure 3 illustrates this for the Hadley Centre's first transient-response, climate-change experiment. In addition to the slow start to the globally-averaged warming response, it also shows the northern hemisphere warming faster than the southern hemisphere. This occurs partly because of the stronger climate feedback mechanisms over land areas and partly because the southern hemisphere is dominated by the high thermal inertia of its oceans. The effects of this cold start made it difficult to ascribe calendar years to the simulated years of the transient-response, climate-change experiments. However, as in IPCC (1990), simpler models (such as the box-diffusion-upwelling and energy-balance models) calibrated against the CGCMs were used to make such projections.

More attention was also being given by this stage to the analysis of variability in the CGCM experiments and of the implications for detecting global change. Indeed, evidence was mounting that models were capable of exhibiting reasonably realistic levels of atmospheric variability on interannual, decadal and even longer timescales, at least on the global scale.

In IPCC (1990) it was recognised that sulphate aerosols could exert a significant negative forcing on climate but this was not well understood or quantified. IPCC (1992) confirmed the view that the cooling effects of sulphate aerosols were likely to be most noticeable around and downwind of the industrial regions of the northern hemisphere and ought to be represented in CGCMs. However, it was by no means clear how this could be done in a meaningful way. Preliminary experiments were being carried out using simpler models calibrated against the CGCMs, the results from which were instructive and suggestive of the likely effects of sulphate aerosols; but experiments needed to be done with the full CGCMs. An additional source of negative forcing was identified in the depletion of stratospheric ozone due to halocarbons.

The existence of strong correlations between characteristics of the solar cycle and global mean temperature had also been reported but it was argued that no firm conclusions regarding the influence of solar variability on climate change could be drawn. A new set of updated scenarios was also defined for use in modelling studies.

A full discussion of all these modelling issues in the context of the Hadley Centre's first transient climate change experiment are recorded in the series of papers by Murphy (1995 a,b) and Murphy and Mitchell (1995).

(b) Radiative Forcing of Climate Change 1994

IPCC (1994) on the radiative forcing of climate change confirmed the ability of greenhouse gases to affect the climate system by changing the radiative balance of the atmosphere. It also provided much improved estimates of forcings by aerosols and established sulphate aerosols as a secondary, but potentially important, influence on climate, although the extent of their radiative effects remains considerably more uncertain than that of the greenhouse gases. Estimates of the global distribution of the atmospheric cooling flux from the direct scattering effects of industrial sulphate aerosols showed this to be commensurate globally with the magnitude of the estimated enhanced greenhouse effect. Locally, particularly in the Northern Hemisphere, it can be very large, the cooling being confirmed as strongest in localised regions over and downwind of the heavily industrialised areas.

Another major new result in the context of both observations and modelling was the study of the global climatic impact of the eruption of Mt. Pinatubo in The Philippines in June 1991. This thrust large quantities of aerosol, ash and dust high into the atmosphere. It was predicted (Hansen *et al.* 1992) that this would cause a measurable reduction in global temperatures, lasting a few years, with a short-lived maximum value of about 0.5K. This is about the same magnitude as the observed global warming since the beginning of the century. These predictions have since been verified by independent analyses of the surface and tropospheric temperatures observed since the eruption (see Parker *et al.* (1996)). The correlations between the predictions and the independent analyses are highly significant and very striking. This natural event not only gave new insight into, and a quantification of, one of the natural causes of relatively short-term variability in the global temperature record but also provided a useful test of global models, leading to increased confidence in their capabilities.

(c) The IPCC Second Scientific Assessment 1995

IPCC (1995) contains several references to progress and achievements with climate modelling that had clearly influenced the wider IPCC review process. Equally importantly, it also highlights remaining uncertainties and identifies the highest priorities for future work in this context.

Radiative forcing was reviewed extensively in IPCC (1994) and the most significant advance by IPCC (1995) was an improved understanding of the role of aerosols and their representation in CGCMs. In particular, considerable progress had been made in distinguishing between natural and human influences on climate (see, for example, the references above to studies of the climatic impact of the eruption of Mt. Pinatubo and the fuller discussion of global average climate forcing and temperature response since

1750 by Rowntree (1998)). Allowing for the effects of sulphate aerosols in addition to greenhouse gases has led to more realistic estimates of human-induced radiative forcing and these have been used in a small number of CGCMs to provide new and more complete simulations of the human-induced climate-change 'signal'. The Hadley Centre was the first to use such a CGCM to simulate and predict human-induced climate change from 1860 to 2100 (see Mitchell *et al.* (1995), Mitchell and Johns (1997) and Johns *et al.* (1997)). For the period 1860 to 1990 atmospheric concentrations of greenhouse gases and sulphate aerosols were estimated from records of fossil fuel consumption. For future projection, greenhouse-gas concentrations were assumed to rise at 1% per annum compound and aerosol concentrations were interpolated using data from the IPCC (1992) 'non-intervention' scenario (IS92a). Note that other future emissions scenarios can be, and are being, used to explore such models' sensitivities and to help establish the range and uncertainty of possible future projections of climate change

When the direct effect of aerosols is allowed for in model simulations alongside that of increased greenhouse gases, the resulting spatial distribution of surface temperature change, and its global average, are closer to the observed changes over the past century. This has been demonstrated by a series of evolving modelling studies, culminating in those with CGCMs discussed in IPCC (1995). The resulting patterns have characteristics quite distinct from those produced with greenhouse gases only and have provided new avenues for establishing a fingerprint of climate change due to human influence. In particular, there are local regions of cooling or very little warming over northern continental regions. These reflect the regions of high aerosol concentrations and emphasise that locally their cooling effect can overcome the warming arising from increased greenhouse gases. However, globally, the greenhouse-gas warming dominates the aerosol cooling. The effects of anthropogenic aerosols have also substantial impacts on projections of climate change. In particular, the spatial and temporal distributions of aerosols greatly influence regional projections, which are therefore more uncertain.

A further major area of progress was the shift of focus from studies of global-mean changes to comparisons of modelled and observed spatial and temporal patterns of climate change. Also, earlier results were confirmed and consolidated. For example, information was now available on both the timing and spatial patterns of human-induced climate change from more than 18 transient-response experiments in which CGCMs had been driven by past and/or projected future time-dependent changes in carbon dioxide concentration (used as a surrogate to represent the combined effect of carbon dioxide and other well-mixed greenhouse gases; 'equivalent carbon dioxide'). Also by this stage some ensembles of transient-response, climate-change experiments were being produced; *i.e.* several runs with identical forcing but slightly different initial climate states. Thus, better definition of the expected climate response to increasing greenhouse gases and aerosols was being gained. However, important uncertainties still remain and no CGCM had yet incorporated the full range of anthropogenic influences.

The results from the most recent CGCM, transient-response, climate-change experiments which included the effects of both greenhouse gases and aerosols made a major impact on the issues of detection and attribution of climate change. Pattern-

based studies, in which modelled climate responses were compared with observed ('geographical, seasonal and vertical') patterns of atmospheric temperature change began producing more convincing evidence for the attribution of human influence on climate. Although the ability to quantify this influence remained limited, this work led to the claim in IPCC (1995) that, **'nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate'**. Given the IPCC's requirement to achieve a widespread consensus for any of its pronouncements, this represented a major shift and firming of its view on the evidence for a human influence on recent climate.

Much new research has been done even since the publication of IPCC(1995) to strengthen that claim and I now refer to the results achieved.

(d) Detection and attribution of climate change

Detection and attribution studies seek to distinguish between human and natural influences on climate. IPCC (1995) defines detection as the process of demonstrating that an observed change in climate is highly unusual in a statistical sense, but does not provide a reason for the change. In contrast, attribution is the process of establishing cause and effect relations, including the testing of competing hypotheses. So, in order to answer the question, 'Can recent changes in global climate be attributed, at least in part, to human influence?', it is necessary to first determine how indeed the climate has changed and if this change is unusual (in a statistical sense). Having monitored globally how the climate has changed, it is then necessary to compare that change with our best estimates of natural variability in order to decide if it is unusual.

Because measurements are not available for long enough, CGCMs are now being used to simulate a thousand years or so of global climate and the maximum range of variability in any (approximately 140-year) period is taken from that simulated record to provide a surrogate for the natural climate variability. Such an example is given in Fig. 4; it can be seen clearly that, if that model adequately simulates the natural variability of the real climate then the past couple of decades have indeed been unusually warm. As best it can be judged, state-of-the-art CGCMs do indeed simulate realistic levels of natural variability on a wide range of temporal and spatial scales. Changes in solar output and volcanic dust both contribute to natural variability and estimates of the temperature changes due to these factors since the middle of the last century can also be provided by the models.

Having established the unusualness of the recently-observed global warmth, the technique then is to model simulated change due to human forcing in a CGCM and to compare the results with our best observational analyses. Before we can claim to have detected a human influence on the recent climate we must first assess and rule out the likelihood that any such changes could be due to the natural internal variability of the climate system or to changes in natural forcings both internal and external (*e.g.* solar, volcanic).

CGCMs are now being run with factors, both natural and human, which will have influenced the climate since 1860: natural variability (which is inherent in the model), changes in solar output and volcanoes, and human-induced changes in the concentrations of greenhouse gases (including ozone) and sulphate aerosols. Figure 5 is again such an example from the Hadley Centre and shows that the change in global temperatures since 1900 simulated by the climate model is in broad agreement with those actually observed. Although this suggests that we are beginning to understand the reasons (including human influences) for temperature changes over the last 140 years, it does not exclude the possibility that this agreement is partly fortuitous. There are many possible combinations of these forcings that could yield the same simulation of the observed global mean temperature change. Some combinations are more plausible than others, but relatively few data exist to constrain the range of possible solutions.

Some of the human influences, such as sulphate aerosols, have strong regional effects on climate. So, in addition to looking at global averages, it is necessary to look also at the evolution of the global geographical patterns of temperature changes since the turn of the century. Statistical tests show that the predicted 'fingerprint' of change expected from human activities can be seen in recent decades, but is absent in earlier years. To complete this type of analysis, observations are also compared with model simulations through the depth of the atmosphere (see Fig. 6). The observed patterns of temperature change, both across the surface of the Earth and through the depth of the atmosphere, can only be explained satisfactorily by including the influence of human activities, particularly emissions of greenhouse gases and sulphur.

In summary, global temperature is continuing to increase and has recently risen beyond the estimated range of natural variability. This new research, following on from IPCC (1995), gives increasing confidence that human activities have contributed, at least in part, to the global temperature rise witnessed in recent decades. Indeed assessments of statistical significance of the observed global mean surface air temp trend over the last century have used a variety of new estimates of natural internal and externally-forced variability. These are derived from instrumental data, palaeodata, simple and complex climate models, and statistical models fitted to observations. Most of these studies have detected a significant change and show that the observed warming trend is unlikely to be entirely natural in origin. For further and fuller details see, for example, Santer *et al.* (1996), Hegerl *et al.* (1996, 1997), Tett *et al.* (1996) and Hasselmann (1998).

(e) Coupled models without flux adjustments

IPCC (1995) refers to flux adjustment as 'a dilemma between the pragmatic need to conduct long runs with imperfectly coupled models and the continuing desire to develop the best possible models on purely physical grounds'. This was elucidated further by Kerr (1994) under the more strikingly critical headline, 'Climate modelling's fudge factor under fire'. CGCMs have a tendency to drift away from a realistic climatology, and in many this is counteracted by applying prescribed artificial fluxes of heat, fresh water and, sometimes, momentum, at the ocean-atmosphere

interface in addition to the normally calculated surface exchanges there. The motivation for using this technique is that the modelled climate response to a perturbation, such as increasing greenhouse-gas concentrations, may be incorrect if the simulation of the current climate has significant errors. However, the use of the technique itself introduces some uncertainty, since it does not have a good physical basis. In the face of this 'dilemma', modellers have sought to justify the use of flux adjustments by demonstrating that they do not cause any gross distortion to the climate responses obtained with them (see, for example, Gregory and Mitchell (1997)).

The atmosphere and ocean interact via the interface at the sea surface and the sea-surface temperatures (SSTs) and the sea-ice cover are therefore crucial predictands in a coupled-model simulation. These also depend critically on ocean heat transports. Figure 7 is a simple schematic illustration of how this operates in a CGCM. Forward integration of the atmospheric component produces the surface fluxes of heat (Q), fresh water (P-E; where P is precipitation and E is evaporation) and momentum (τ) that are needed to 'drive' the ocean model and to thereby update the SSTs and the sea-ice cover, which in turn are fed back to the atmosphere model. The ocean's own transports of heat and salinity are denoted schematically (in Fig. 7) by $F_{H,S}$. In any ocean region, in the long-term annual mean, the net surface heat exchange must be balanced by the ocean advection of heat into (or out of) the region. It follows that there will be a net drift in the ocean temperature if the ocean advection and the net surface heating terms do not balance. This in essence is the reason for climate drift in CGCMs. A realistic simulation of both the surface heat fluxes and the ocean heat transports is necessary to reduce such climate drifts in both the SST and sea-ice simulations. A most significant breakthrough has been made in this respect since IPCC (1995), with several modelling groups now having achieved stable and realistic climate simulations without invoking artificial flux adjustments. For early references see, for example, Gent and Bryan (1997) (NCAR), Gordon *et al.* (1997) (Hadley Centre), and Madec and Delecluse (1997) (Laboratoire d'Océanographie Dynamique et de Climatologie, Paris). The first such claim, from the NCAR modellers, was also highlighted by Kerr (1997) under the telling banner, 'Model gets it right - without fudge factors'.

Earlier versions of the Hadley Centre CGCM, including that used in IPCC (1995), required seasonally-varying flux adjustments of the ocean-surface heat and fresh-water fluxes (see Johns *et al.* (1997)). However, over the past few years of continuous model development a number of changes have been introduced to achieve a CGCM (labelled HadCM3) which produces a stable and realistic long control climate simulation without the use of flux adjustments. I shall indicate some of the qualities of that model from early results provided by courtesy of Dr C Gordon and his co-workers (C. Cooper, C. A. Senior, H. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell and R. A. Wood; private communication, but see also Gordon *et al.* (1998)).

HadCM3 is an updated version of the model (HadCM2) described by Johns *et al.* (1997). The atmosphere component remains part of the Meteorological Office's Unified Model suite for both numerical weather prediction and climate studies (Cullen 1993). It has a horizontal resolution of 2.5^0 x 3.75^0 on a latitude-longitude grid and has 19 vertical levels using a hybrid vertical co-ordinate. Major improvements to the

physical representations in this model include: a new radiation scheme (Edwards and Slingo 1996); a parametrization of a simple aerosol climatology (Cusack *et al.* 1998); convective momentum transports (Gregory *et al.* 1997); a new land-surface scheme (Cox *et al.* 1998); a new gravity-wave drag scheme (Gregory *et al.* 1998); a parametrization of orographic drag (Milton and Wilson 1996); and several changes to the parametrization of clouds based on the work of, for example, Gregory and Morris (1996) and Martin *et al.* (1994). There have also been significant changes to the atmospheric boundary layer scheme in the model, and a number of minor changes.

The ocean component is also substantially different to that used previously in Hadley Centre CGCMs. It has a horizontal resolution of 1.25^0 x 1.25^0 on a latitude-longitude grid and has 20 vertical levels. The higher horizontal resolution, and consequent lower 'numerical' viscosity, lead to considerably more realistic simulation of the ocean circulation and a substantial increase in the poleward heat transports in the ocean model. Horizontal mixing of tracers is based on the Gent and McWilliams (1990) scheme which seeks to parametrize the effects of the finer-scale ocean eddies. Another important new feature is a simple representation of sill overflows across the Denmark Straits and Iceland-Scotland Ridge and a parametrization of the outflow of water from the Mediterranean (Roether *et al.* 1994). The sea-ice model uses a simple thermodynamic scheme and contains parametrizations of ice drift and leads (Cattle and Crossley 1995).

The component models are coupled once per day. The atmospheric model is run with fixed SSTs through the day and the various forcing fluxes are accumulated each atmospheric model timestep (*i.e.* every 30 minutes). At the end of the day these fluxes are passed to the ocean model which is then integrated forwards in time. The updated SSTs and ice extents are then passed back to the atmospheric model (recall Fig. 7). A coupled model control simulation has been integrated for over 500 years, from an initial state based on climatological ocean temperatures and salinities for September (Levitus and Boyer 1994; Levitus *et al.* 1994) and a corresponding atmospheric state.

The timeseries of global mean SST anomaly and top of the atmosphere (TOA) flux are shown in Fig. 8. The SST anomaly is defined as the difference between the model SST and the Hadley Centre's widely-used Global sea-Ice and Sea Surface Temperature (GISST) dataset (Rayner *et al.* 1996). The trace-gas concentrations used in the model are pre-industrial so the modelled SSTs are expected to be about 0.3K colder than the present-day GISST temperatures. In fact, the global SST in the coupled model remains within 0.3K of climatology over the full 550 years or so of the simulation and although there is considerable interannual and interdecadal variability evident in the timeseries there is little sign of any long-term climate drift. The major characteristics of the geographical pattern of simulated SST are also very stable after the first few decades. The TOA flux is also generally less than 0.5 Wm^{-2}; over most of the experiment it is negative, indicating a net cooling of the climate system in the model. Also, after an initial short period, the timeseries of global mean sea-ice area and volume show remarkable stability and, overall, the sea-ice distributions are well simulated in both hemispheres. These and other aspects of this model's ability to simulate realistic SSTs, sea-ice extents, surface heat and momentum transports, and ocean heat transports, all of which are critical to achieving a realistic and stable simulation, are discussed more fully by Gordon *et al.* (1998).

Figure 9 illustrates the differences between the modelled SSTs and the GISST climatological SSTs averaged over the years 81-120 of the integration. This pattern and the magnitudes of the differences remain effectively constant throughout the rest of the 550 years of the experiment. Over most of the ocean this CGCM is simulating the SSTs to within 2K of their observed values after over 500 years of model integration. The capability to start from the 'Levitus' observed ocean state and to maintain this without large drifts over 500 years is one of the model's most notable successes. Figure 9 also shows a comparable SST anomaly field from a corresponding 'control' experiment with the previous Hadley Centre CGCM (HadCM2) when no flux adjustments were used. The general and significant reduction in SST errors achieved by HadCM3 is clearly evident. There remain, however, some notable regions in the HadCM3 simulation where the differences between the model and climatology are considerably larger than 2K, and these are the focus of analysis and further model development.

Gordon *et al* (1998) attribute the success of their particular CGCM to the improved simulation of both the surface heat fluxes and the poleward ocean heat transports in the coupled system, which in HadCM3 are in broad agreement with observational estimates. However, they have no simple diagnosis and explanation of which particular model improvements have brought about this success. Rather, they identify a number of important developments in the atmosphere, ocean, sea-ice and land components of their fully-coupled climate model that have been painstakingly developed, tested and implemented to bring about improvements in both the individual components and in the coupled model itself. This same model (HadCM3) has already been used for transient-response climate-change experiments (J. F. B. Mitchell, T. C. Johns and C. A. Senior; private communication). Figure 10 shows that it predicts a change in global mean temperature over the next 100 years due to increases in greenhouse gases, of some 3K, very much in line with the previous, flux-adjusted model and near to the central estimate given in IPCC (1995). Note that the flux-adjusted model (HadCM2) result is the mean from an ensemble of experiments, hence it shows less variability than the single experiment using HadCM3.

4. FUTURE PROBLEMS, PRIORITIES AND PROSPECTS

There is a complex chain of processes in the atmosphere and other components of the climate system which leads from emissions to climate change, and ultimately impacts. This is reflected in the sequence of modelling steps required to explore the climatic responses obtained from a range of emissions scenarios. For a given emissions scenario, it is necessary to invoke models of the carbon cycle, sulphur cycle, and other aspects of chemistry to convert emissions into atmospheric concentrations (where possible). At present this has to be done mostly 'off-line'; *i.e.* the processes involved are not all included explicitly in the CGCMs being used for climate-change studies. The concentrations of greenhouse gases and aerosols must then be converted into an atmospheric forcing via a radiation model. The degree to which this is done explicitly in the CGCM or 'off-line' depends much more on the particular greenhouse gas or aerosol being considered, and the particular CGCM being used. The CGCM then

evaluates the climate response to the particular radiative forcing applied, from which the impacts are ultimately inferred.

There are therefore several, complicated modelling steps in going from emissions to the corresponding climate response, and ultimately the impacts resulting from the climate change. Not only do we need a reliable way of modelling the processes involved, we also need to understand and allow for the feedback processes in the system. There are physical feedback loops such as that related to, for example, the melting of sea-ice, which feeds back directly into the forcing, and also feedbacks from the climate change onto the sources and sinks of the greenhouse gases. In addition, climate change may impact on social and economic factors which, in turn, will feed back on the emissions scenario. This illustrates how wide-ranging and inter-related in a disciplinary sense is the whole challenge of climate prediction.

In this address I have tried to demonstrate, albeit selectively, that significant progress has been, and is still actively being, made in each of these areas. In particular, the Hadley Centre's second coupled atmosphere-ocean model (HadCM2) has now been used for a wide range of climate-change studies as illustrated schematically in Fig. 11, and the model currently being used for such studies (HadCM3) can be run without flux adjustment, has higher resolution in its ocean component, and includes an explicit sulphur cycle. However, many factors currently still limit our ability to understand, detect, attribute and predict climate change. From a modelling perspective, the highest priorities between now and the next full Scientific Assessment planned by IPCC (in 2000/01) are:

(i) the continued development of improved CGCMs, with higher resolution and better coupling of the atmosphere, ocean and land components;

(ii) the development of improved regional simulation and prediction through the use of higher-resolution regional climate models (RCMs) 'nested' within global GCMs, and other techniques, such as 'statistical downscaling' from large to smaller scales;

(iii) improvements in the representations of the smaller-scale (i.e. sub grid-scale) processes in CGCMs and their regional counterparts. This problem is known generically as 'parametrization'. Particularly important challenges remain still in relation to feedbacks associated with clouds, oceans, sea ice, vegetation and the hydrological cycle in general;

(iv) the development of methods for the detection and attribution of climate change. This requires detailed studies of both observed and modelled climate variability on a wide range of temporal and spatial scales;

(v) improved models of aerosol forcing. This should lead to improved climate projections for different scenarios which include both greenhouse gases and aerosols;

(vi) the development of models with better representations of important chemical and biological processes both on land and in the oceans. There is a need to include more explicit modelling of atmospheric chemistry and of the carbon and other biogeochemical cycles within (or off-line from) the CGCMs; and

(vii) investigation of non-linear processes of the climate system, to try to pre-empt 'surprises'; *e.g.* those associated with possible rapid circulation changes in the North Atlantic or with feedbacks resulting from changes in the terrestrial ecosystem.

The prospects of making significant progress remain high. There is much to be done that can be done - and will be done if appropriate resources are forthcoming. At the Hadley Centre, we do in fact have a very clear and detailed strategy for model development and use, in order to meet the needs of our Government (and others) for advice on climate change which is compatible with the collective progress in scientific understanding as stimulated and reflected by the IPCC process. Table 2 indicates the evolution of Hadley Centre CGCMs to date, with a glimpse forward to the next planned version, HadCM4. The atmosphere is the most developed component of such models: but plenty of challenges remain even in that area. We now have considerable experience and success in dealing also with many land, ocean and ice processes. The current and near future challenges and aims relate to interactive carbon-cycle and atmospheric chemistry modelling.

The model we hope to use for the 2000/01 IPCC assessment, HadCM4, is likely to have higher vertical resolution in the atmosphere component, and will include a carbon cycle model. Note that our suite of models includes off-line models for the sulphur cycle, atmospheric chemistry, and the ocean and terrestrial components of the carbon cycle. We are also continuing to develop and use RCMs, with a 50km horizontal grid-length, and applicable to different parts of the globe.

However, the wide range of estimates of climate sensitivity remains a major concern. Recall that the likely equilibrium response of global surface temperature to a doubling of equivalent carbon dioxide was estimated in 1990 to be in the range 1.5-4.5K, with a best estimate of 2.5K. The range of estimate arises from uncertainties in climate models and in their internal feedbacks, particularly those concerning clouds and related processes. The processes involved in cloud-radiation interaction are complex and, although there has been considerable progress since 1990 in understanding and modelling them, their uncertainty represents a significant source of potential error in climate simulation. Indeed, IPCC (1995) reports that if clouds and sea ice are kept fixed according to their observed properties, then state-of-the-art climate models would all report climate sensitivities in the range 2-3K. However, modellers continue to demonstrate that physically-plausible changes in cloud distribution could either as much as double the warming expected for fixed clouds or, on the other hand, reduce it by up to 1K. The range in estimated climate sensitivity of 1.5K-4.5K is largely dictated by this uncertainty and IPCC (1995) states that no strong reasons have emerged to change these estimates.

In terms of climate modelling applications, over the next five to ten years we should be aiming to :

(i) reduce the uncertainty in estimates of future climate change. For the same target temperature rise, the currently allowable cumulative emissions to 2100, say, lie in a wide range (650 GtC - 1400 GtC). Planned model improvements (in relation to, for

TABLE 2. HADLEY CENTRE COUPLED OCEAN-ATMOSPHERE CLIMATE MODELS

	HadCM1 (1992)	HadCM2 (1995)	HadCM3 (1997)	HadCM4 (1999)
Atmosphere:				
Resolution	2.5° x 3.75°	2.5° x 3.75°	2.5° x 3.75°	2.5° x 3.75°
Layers	11	19	19	38
Cloud μphys	7μm water, 30μm ice	7μm water, 30μm ice	f(LWC, airmass),30μm	explicit ice/water Non-spher ice=f(T)
Dynamics	Eulerian	Eulerian	Eulerian	Eulerian
Ocean:				
Resolution	2.5° x 3.75°	2.5° x 3.75°	1.25° x 1.25°	1.25° x 1.25°
Layers	17	20	20	20
Flux adjustment?	seasonal heat + water+sea-ice	seasonal heat + water	no	no
Sea ice	thermodynamic	leads, ice drift	leads, ice drift	+ wind effects
Run time	Cyber	2y/d C90 1cpu	4y/d 72PE T3E	
Climate sensitivity	2.8K	3.2K	3.3K	
Forcing	CO2 only	CO2 + SO4 albedo	All ghg + SO4 C cycle (1998)	All ghg, SO4 C Cycle
Other models:	HadSCM (sulphur cycle model); STOCHEM (atmospheric chemistry); HadOCC (ocean carbon cycle); TRIFFID (land carbon cycle); HadRCM (regional climate model, 50km grid, Europe, India)			

example, clouds, oceans, and the carbon cycle) should enable us to narrow the current range of uncertainty;

(ii) provide proper statistical estimates of uncertainty in predictions. Current estimates are not statistically based, so cannot be used in risk analyses. Calibrating climate simulations against observations would allow uncertainties to be assessed statistically for the first time;

(iii) demonstrate more confidence in estimates of the human component of recent climate change. Tougher greenhouse-gas policies will only be acceptable if they can be justified by firmer science. Attribution needs to be pursued through more comprehensive models, better observations and better statistical techniques;

(iv) provide more detailed estimates of regional climate changes, and changes in extreme weather. Impacts of climate change will be felt regionally and largely through extreme events. Better predictions would allow better costing of impacts and help with adaptation;

(v) identify the potential for rapid climate change. This would help with the definition of what constitutes 'dangerous anthropogenic interference with the climate system' in the UN FCCC Article 2, and hence help determine acceptable levels for the stabilisation of atmospheric greenhouse-gas concentrations;

(vi) assess the potential predictability of climate over the decade ahead. Decadal forecasts would assist industry in planning for the transition to a changing climate and could pre-empt criticism of policy in the event of a cold decade; and

(vii) contribute substantially to IPCC scientific assessments and therefore to the scientific underpinning that is crucial to future Conferences of the Parties to the UN FCCC.

Large and dedicated computing resources remain a prerequisite, and a potential bottleneck, for the further development and implementation of the increasingly complex and comprehensive CGCMs already being planned. In this context, it is worth noting in particular the Japanese proposal to carry out an 'Earth Simulator' Project which aims to simulate a 'Virtual Earth'. The goal is to apply high-level simulation techniques to achieve reliable global-change predictions whilst simultaneously pushing forward high-speed computational technology as rapidly as possible. The stated intention is to deliberately and systematically advance research and development in both hardware (computers) and software (models) in parallel. The 'Earth Simulator' envisaged is a high-performance parallel computer which will have an effective performance characteristic of more than about 5 Tflops and a memory exceeding 4 Tbytes. On this will be run a global-scale high-resolution (10 km) model. These are to be constructed and implemented in planned phases over the next 5 - 10 years.

5. CONCLUDING REMARKS

In the modelling context, a great deal of significant progress has been made since the IPCC's first Scientific Assessment in 1990. The CGCMs being used for predicting climate change are physically-based and becoming increasingly realistic in their simulations of recent climate. All of the key research areas in section 2(d) have been addressed with demonstrable progress and some have been largely resolved; in particular, the cold start and, now it would seem, the need to resort to flux adjustments to avoid climate drift. Also, understanding and quantification of the forcings have been greatly improved and it has been clearly demonstrated that aerosols also influence significantly the projections of possible climate change, at both global and regional scales. Arguably, these recent new insights into human-induced climate change should increase the concern over global warming and climate change resulting from an enhanced greenhouse effect. In providing plausible causes for offsetting the enhanced greenhouse effect during the industrial period we have identified other mechanisms whereby human activity can influence the climate globally and regionally. At the same time, such studies have increased confidence in our modelling capabilities and re-emphasised the need to improve our understanding of the climate and its variability.

However, deficiencies and uncertainties remain, particularly in establishing the actual radiative forcing to apply, the sensitivity of the models to different and new 'parametrizations' and 'feedbacks', and in relation to natural versus human-induced climatic variability. Also, our incomplete understanding of the climate system means that we need to investigate the possibility of rapid, non-linear changes to climate. International collaboration in the IPCC assessments and in the formulation and implementation of programmes such as the World Climate Research Programme (WCRP) and the International Geosphere-Biosphere Programme has enabled problem areas to be identified and scientific priorities to be agreed. Indeed, refinement of climate models remains a major unifying component of the WCRP, requiring scientific and technical advances in a wide range of disciplines. See, in particular, the valuable systematic validation, diagnosis and intercomparison of the performance of atmospheric GCMs carried out in the international Atmospheric Model Intercomparison Project, initiated by the WCRP in 1989 (Gates *et al.* 1998).

In concluding, I wish to stress the importance of the IPCC review process. Its reports are widely accepted by the informed scientific community and by policymakers as the most authoritative and strongly supported statements on climate change ever made by the international scientific community. They are recommended to all who wish to be fully and properly informed about our collective state of knowledge, ***and the uncertainties***, about the complex problems of monitoring and modelling the climate and detecting, attributing and predicting climate change. Equally important, they also identify the highest priorities for future work in this context. The appropriate references are IPCC (1990, 1992,1994,1995).

I end with a quote : *'One of the most marked and important developments in meteorology in the last few years has been the sudden upsurge of interest in the subject of climate and climate change. There is an increasing awareness that climatic fluctuations, unpredictable in magnitude and duration, promise to have greater economic and social impact in the future than in the past, and some concern that man himself may induce inadvertent and irreversible changes. At the same time, ------ the availability of computers capable of executing more than 10 million instructions per second has encouraged the development of complex (though still oversimplified) numerical models for the simulation of global climates and for investigating the likely influence of various natural and man-made perturbations. Although I think that the likelihood of major and potentially catastrophic changes in climate has been grossly exaggerated, the subject is of sufficient potential importance and concern to merit a sustained research programme aimed at determining past and current trends more reliably and at improving our understanding of the underlying mechanisms'.*

These are the opening remarks from Sir John Mason's Symons Memorial Lecture (Mason 1976), delivered to the Society on 17 March 1976. I could have used most, if not all, of them in opening this address. Such a 'sustained research programme' has indeed been conducted and progress has undoubtedly been made in all the areas cited by Sir John. Clearly we do not yet have all the answers, but I am confident that continuing sustained research and development of the climate models, coupled with more systematic monitoring of the climate system, will lead steadily to valuable and reliable predictions of climate change at both the global and the regional scales.

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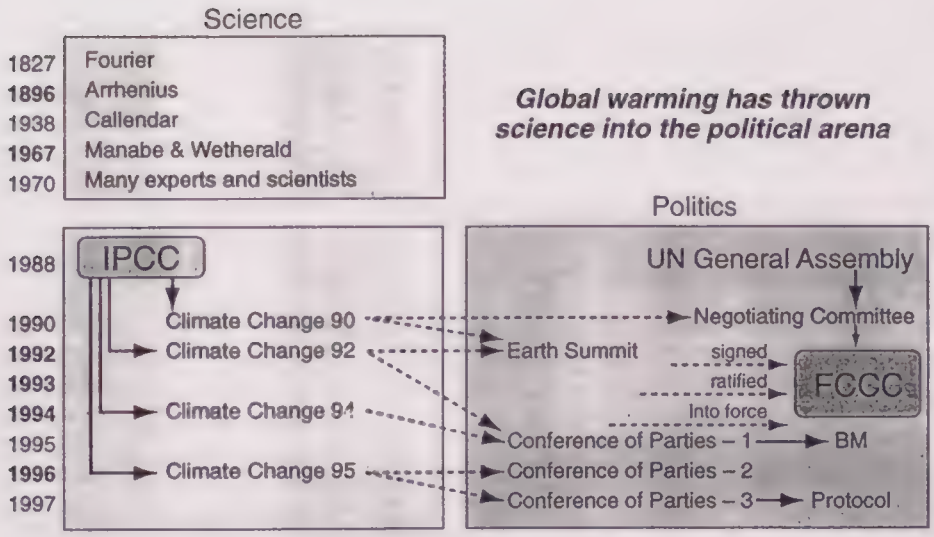

Figure 1. An indication of how the major scientific reports of the Intergovernmental Panel on Climate Change (IPCC 1990, 1992, 1994, 1995) have interfaced with the parallel deliberations of the United Nations Framework Convention on Climate Change (UN FCCC). BM denotes the Berlin Mandate of 1995; the 1997 Protocol is the 'Kyoto Protocol'. The upper frame indicates earlier 'milestones' in the scientific recognition and understanding of the atmospheric 'greenhouse effect'.

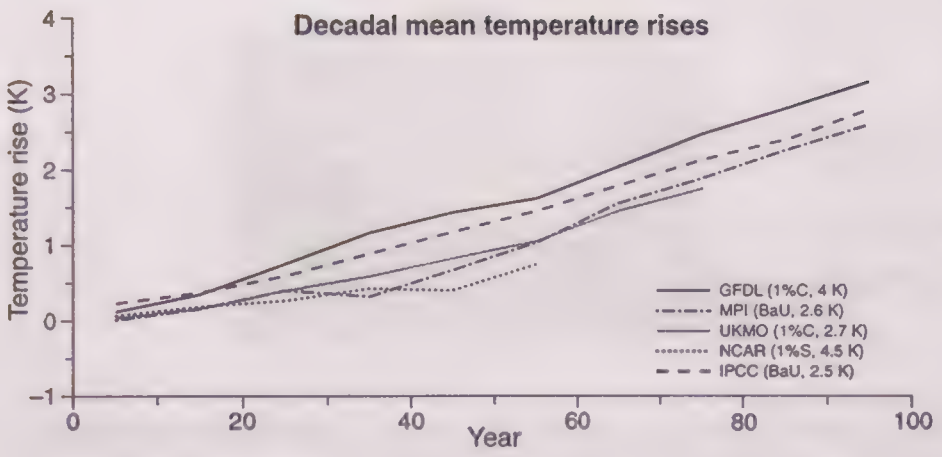

Figure 2. Decadal mean changes in globally-averaged surface temperature in various CGCM experiments (see text for details); the NCAR values are for sea-surface temperatures only. Note that the emissions scenarios employed differ from model to model, as do their climate sensitivities. BaU is the Business-as-Usual scenario (IPCC 1990); 1%C denotes a 1% per annum compound increase in carbon dioxide concentrations; and, 1%S denotes a 1% per annum simple increase in carbon dioxide concentrations. The models' climate sensitivities are the second figure in the brackets in the key, and range from 2.6K (MPI) to 4.5K (NCAR). The IPCC line represents the IPCC (1990) best estimate for a BaU scenario and medium climate sensitivity (2.5K). Adapted from IPCC (1992).

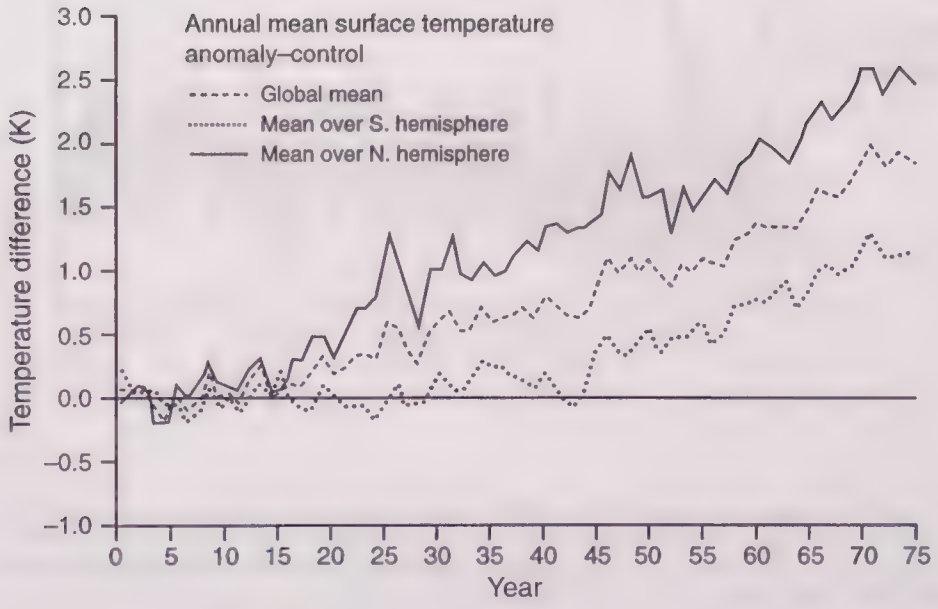

Figure 3. The annually-averaged surface temperature response to a 1% per annum increase in carbon dioxide in the Hadley Centre's first transient-response, climate-change experiment; for the globe as a whole and separately for the northern hemisphere and the southern hemisphere. Adapted from Murphy and Mitchell (1995).

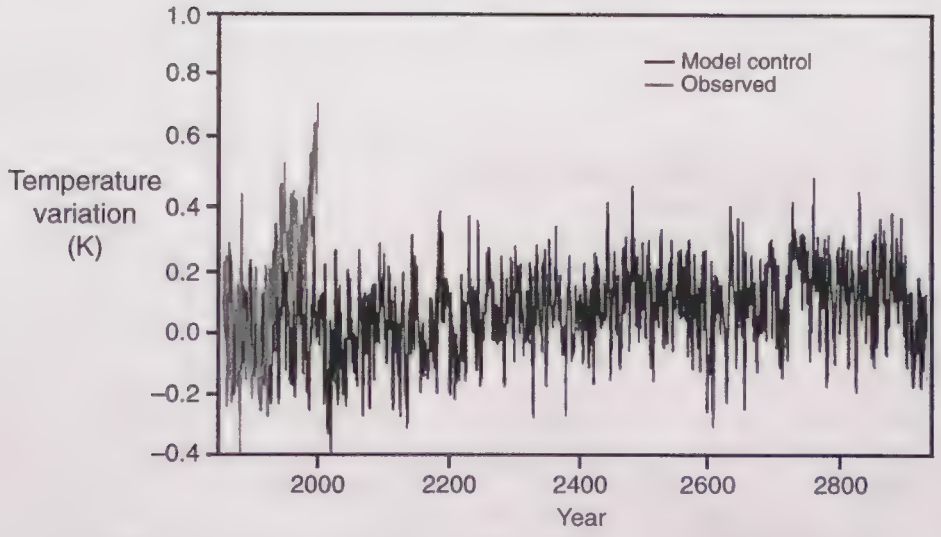

Figure 4. An illustration of the variability in the globally- and annually-averaged surface temperature throughout more than a thousand years simulated by a Hadley Centre CGCM. Also shown is the corresponding timeseries estimated from observations since 1860. (S F B Tett, private communication).

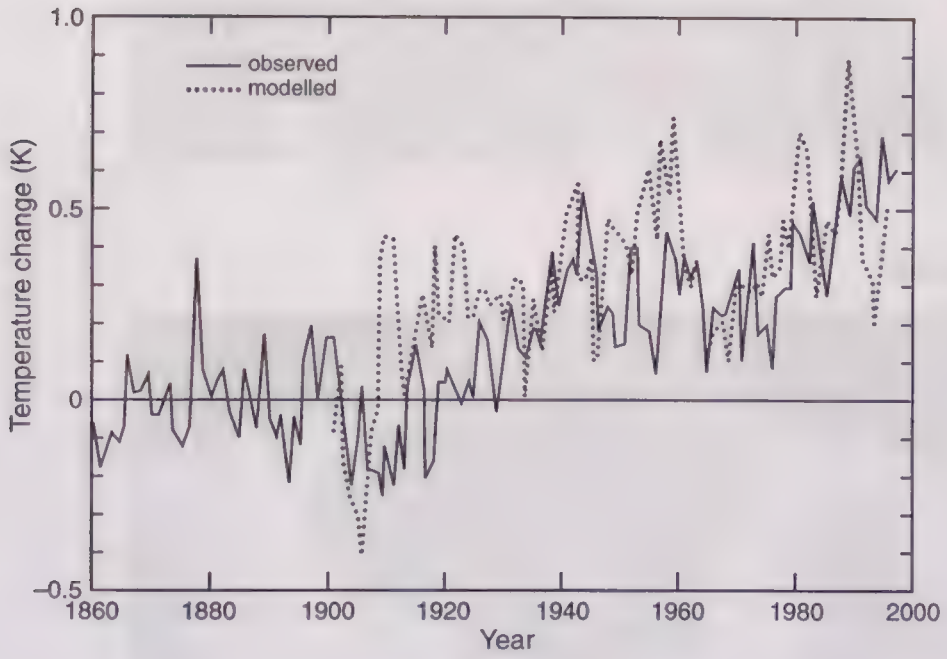

Figure 5. The change in globally- and annually-averaged surface temperatures since 1900 simulated by a Hadley Centre CGCM which includes a range of both natural and human-induced forcing factors, compared with the corresponding observations, shown from 1860.

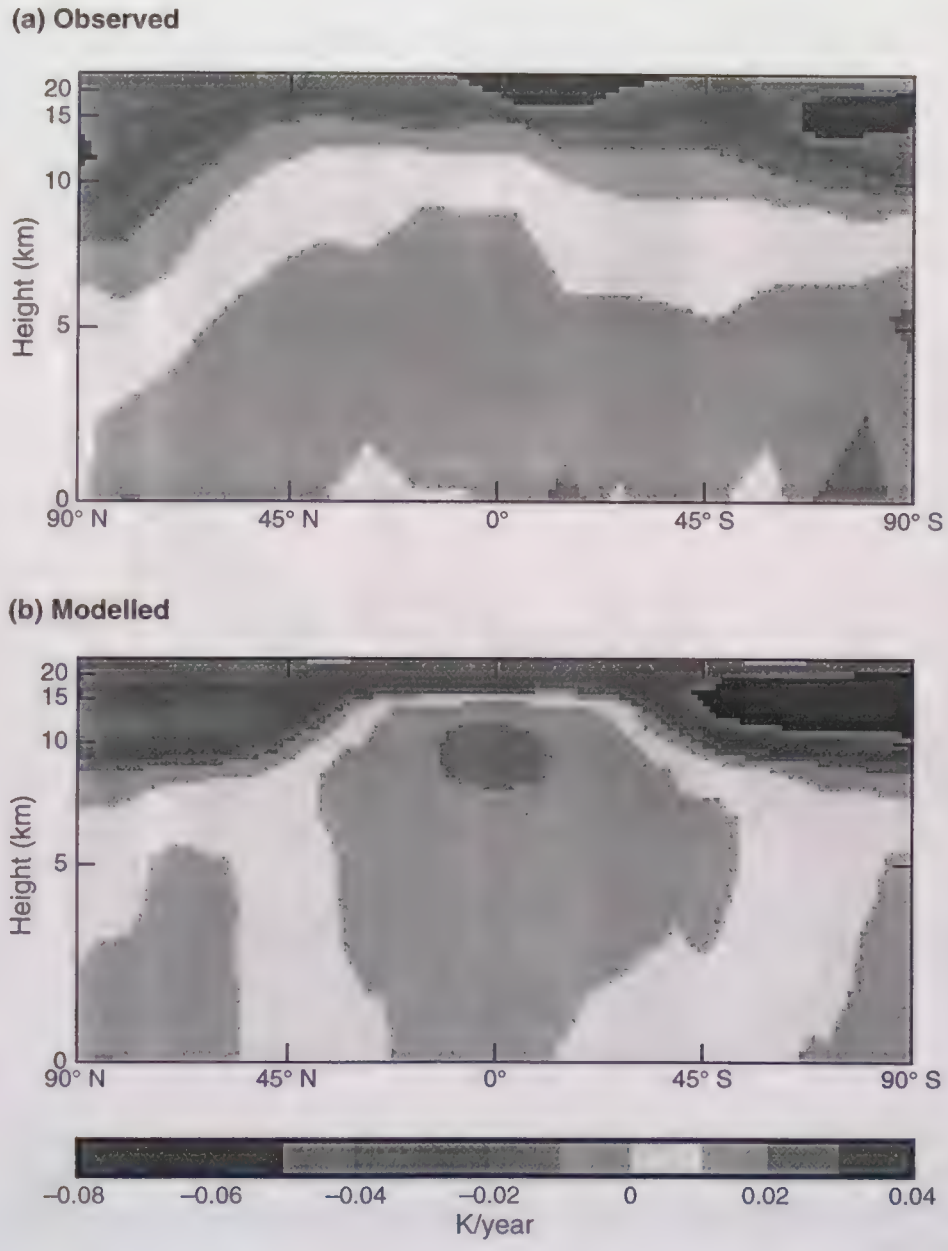

Figure 6. Temperature trends from 1961 to 1996 through the depth of the atmosphere: (a) as observed; (b) as simulated by a Hadley Centre CGCM.

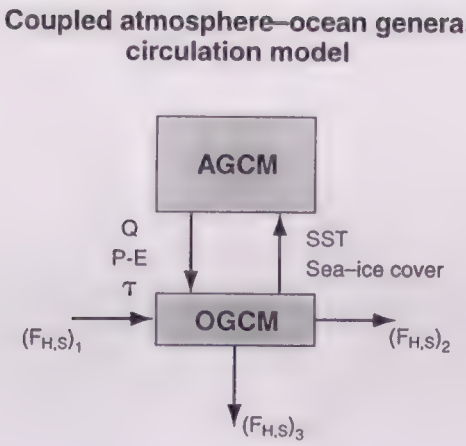

Figure 7. A schematic illustration of how the atmosphere and ocean components of a coupled model interact. See text for details.

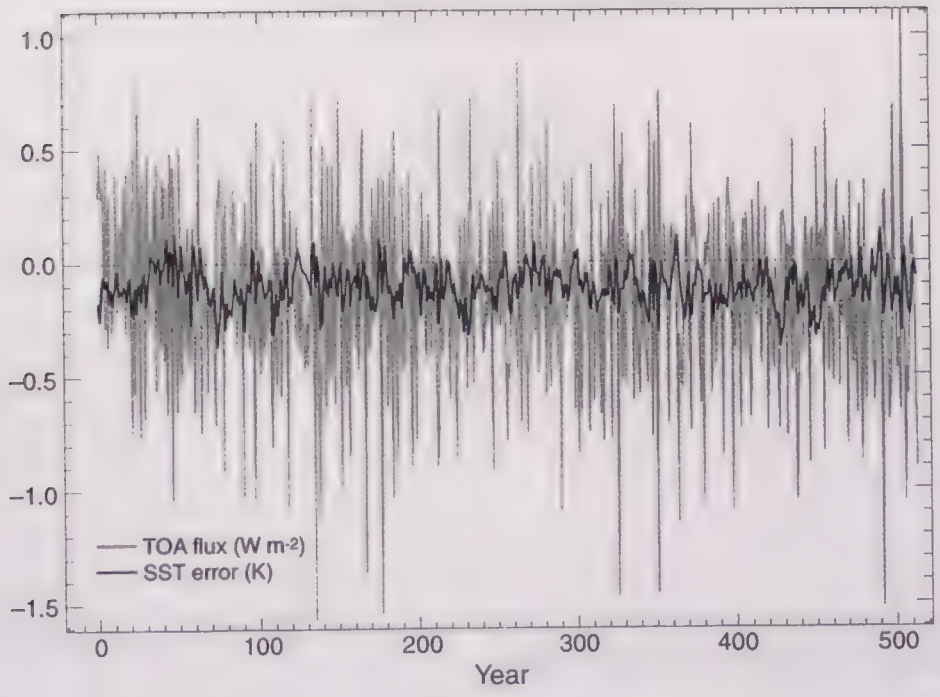

Figure 8. The timeseries of globally- and annually-averaged sea-surface temperature (SST) difference (from the Global sea-Ice and Sea Surface Temperature (GISST) climatology) and the top of the atmosphere (TOA) flux from the control experiment of the Hadley Centre CGCM, HadCM3, run without the use of flux adjustments (Gordon *et al.* 1998).

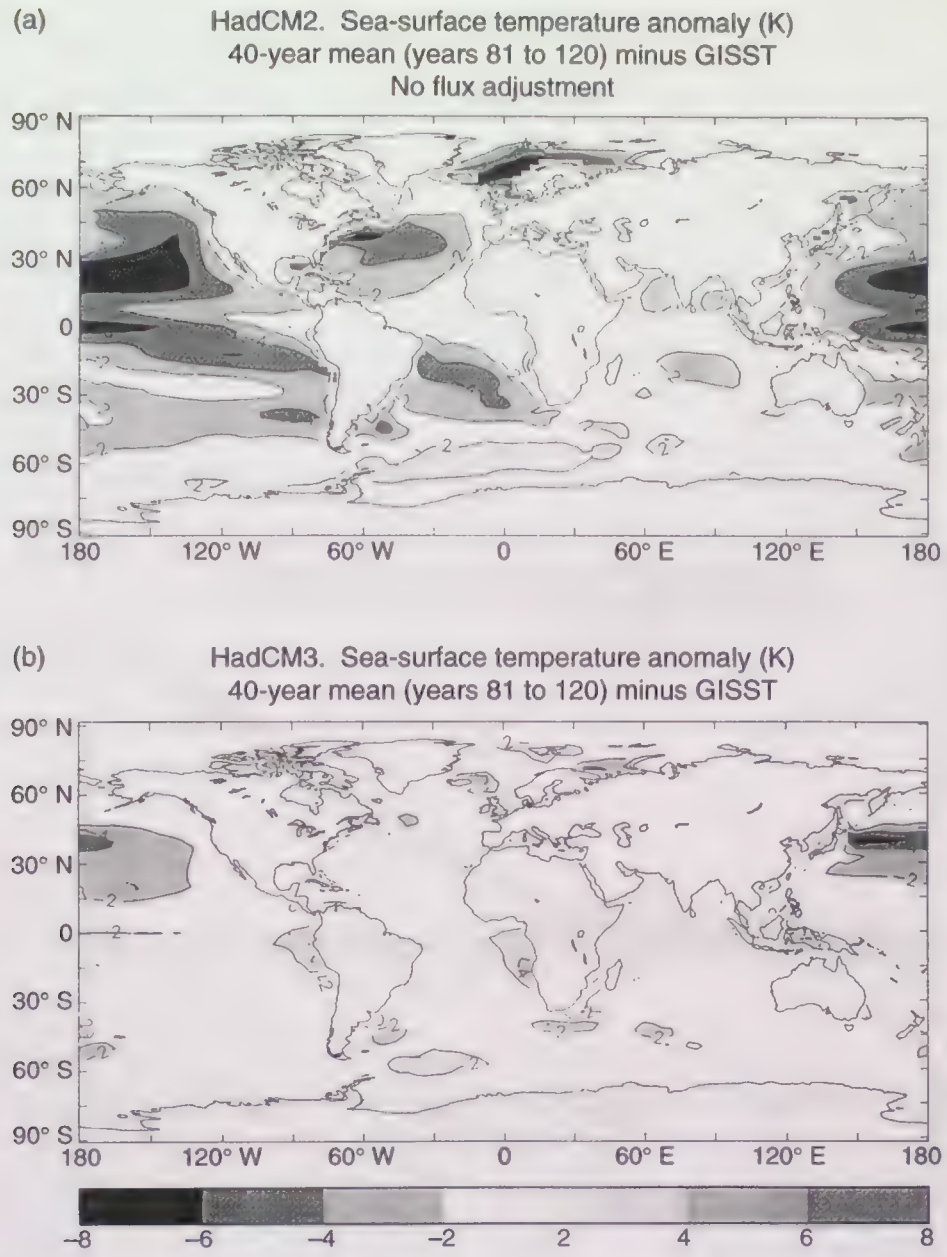

Figure 9. Sea-surface temperature differences between 40-year mean values (years 81-120) derived from Hadley Centre CGCM control experiments and the Global sea-Ice and Sea Surface Temperature (GISST) climatology: (a) for model version HadCM2 run without flux adjustments; (b) for model version HadCM3 run without flux adjustments. (Gordon *et al.*, private communication.)

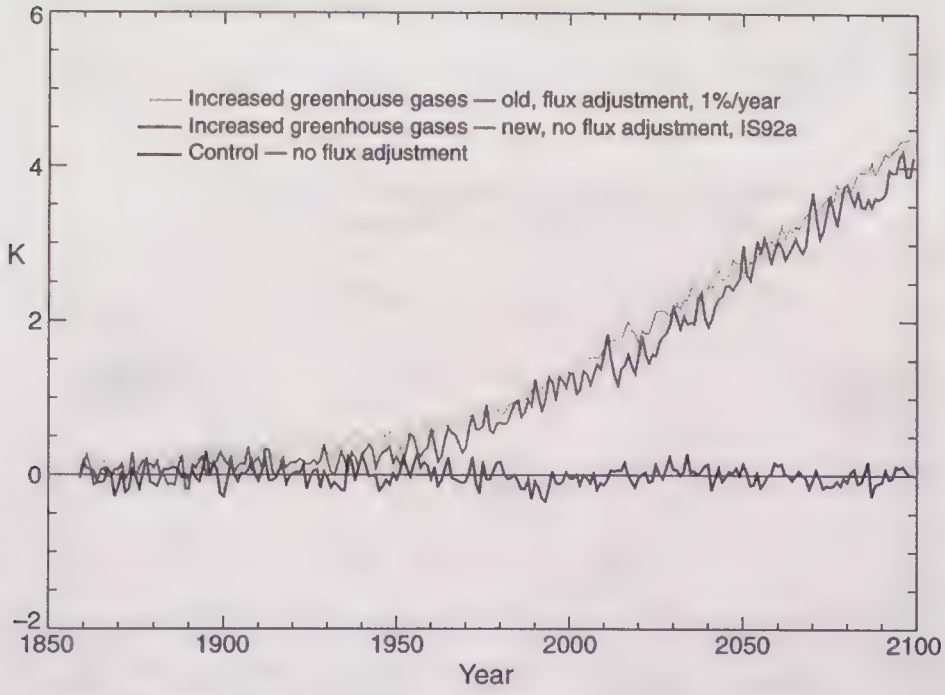

Figure 10. Globally- and annually-averaged surface temperature changes (K) for: (a) the control experiment with model HadCM3 (no flux adjustment); (b) HadCM3 with the IPCC (1992) emissions scenario IS92a used for the future projection; (c) the ensemble-mean response from model HadCM2 (with flux adjustments), which used a 1% per annum compound increase in carbon dioxide for the future projection. (Mitchell *et al.*, private communication.)

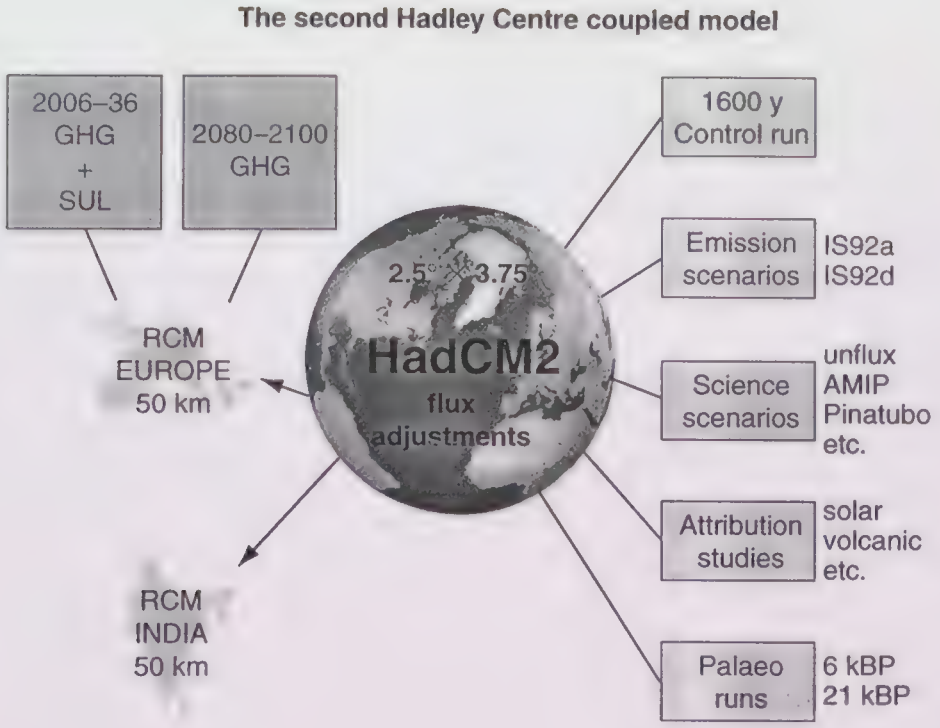

Figure 11. A schematic illustration of the wide range of climate-change studies addressed with the Hadley Centre's CGCM, HadCM2.

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CRTN 5	Dec 1990	A comparison of 11-level General Circulation Model Simulations with observations in the East Sahel. K Maskell
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CRTN 23	Feb 1992	The temporal evolution of Equatorial Currents in the Indian Ocean D L T Anderson, D J Carrington, R A Corry and C Gordon
CRTN 24	Feb 1992	Stratospheric analyses provided by the U.K. Meteorological Office M J Bailey, A O'Neill and V D Pope

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CRTN 29	Jun 1992	A tropical ocean model with reduced physics M K Davey
CRTN 30	Jun 1992	International Temperature Workshop, Boulder, Colorado, USA, 16 January 1992 Edited by D E Parker
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CRTN 85 Jun 1998 Climate Modelling : Achievements and Prospects

D J Carson